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The Principal Investigator has concentrated mainly on Project 2 during this initial support period. In late August 1989, the preliminary results were presented in a paper given at the Eleventh International Conference on Free Electron Lasers (see Digest of paper, Appendix E). Further results including a guide magnetic field were presented in a second paper given at the Thirty-First Annual Plasma Divisional Meeting of the American Physical Society held in November 1989 (see abstract, Appendix F). Two important developments have been (1) the recognition that the conditions for minimal axial degradation and for immunity to saturation by trapping (Research Objective 6) can be satisfied simultaneously, and (2) a numerical example of a 33 TW submicron radiation source (see Appendix D, Submitted paper).

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Participation of Principal Investigator

The Principal Investigator for this grant, Professor Shayne Johnston, devoted 50% of his time during the academic year 1989-90 and 2.0 summer months during Summer 1990 to this grant. The 50% release time from teaching duties was honored by the University and contributed to the hiring of an additional physics faculty member. On the Departmental level, a separate room was made available to the PI for the establishment of a computer research laboratory.

Participation of Students

1. Two undergraduate physics majors were active participants in the research. In particular, they each received academic credit (Special Topics in Physics, 3.0 credit hours) in the Fall Semester 1989 for supervised readings in the field of free-electron lasers. One of these students, Mr.Quinton L. Williams, was a senior who graduated with a B.S. degree in physics in Spring 1990 and has now gone on to graduate study in physics at Georgia Tech. The other student, Mr. John E. Foster, was selected by the University in Fall 1990 as its sole HEADWAE Student Honoree, i.e., its Student-of-the-Year, in recognition of his outstanding scholarly and extra curricular record. They both did a fine job rendering computer support.

2. A graduate student in computer science, Mr. Vijaykanth R. Tummalapally, also participated in the research. In particular, he was very helpful in planning and implementing the acquisition of computer hardware and software. Mr. Tummalapally will complete the requirements for the M.S. degree during Fall 1990.

Progress Towards Research Objectives

The research objectives of the three component projcts of this grant are summarized in Appendix B. The progress towards these objectives is summarized as follows:

Project 1: Sideband Control by Optical Guiding

During the Spring Semester 1990, Mr. Quinton Williams and Mr. John Foster performed numerical studies of parametric and forcing excitation of nonlinear oscillators (Research Objective 6). The results of these investigations are interesting but incomplete, i.e., not yet publishable.

Project 2: A Path to Ultra-High-Power Free-Electron Lasers

The Principal Investigator has concentrated mainly on Project 2 during this initial support period. In late August 1989, the preliminary results were presented in a paper given at the Eleventh International Conference on Free Electron Lasers (see Digest of paper, Appendix E). Further results including a guide magnetic field were presented in a second paper given at the Thirty-First Annual Plasma Divisional Meeting of the American Physical Society held in November 1989 (see abstract, Appendix F). In addition, two papers were prepared

for publication. The first, entitled "Higher-Power Free-Electron Lasers", was published in Nuclear Instruments and Methods in Physics Research A296, 532 (1990) (see Appendix C). The second, entitled "A Path to Ultra-High-Power Free-Electron Lasers", was submitted to Physical Review A in April 1990 and is currently being revised (see Appendix D).

Two important developments have been (1) the recognition that the conditions for minimal axial degradation and for immunity to saturation by trapping (Research Objective 6) can be satisfied simultaneously, and (2) a numerical example of a 33 TW submicron radiation source (see Appendix D, Submitted paper).

Finally, the recent acquisition by the PI of an IBM RS6000/Model 530 workstation (through a different grant) has expanded the future scope of this work to include particle simulations. Such simulations are needed to study properly the principal constraint in the proposed scheme, namely, the potential degradation of the microbunches due to both the initial electron energy spread and the energy spread induced subsequently by electrostatic repulsion.

Project 3: The Orbital-Instability Operating Point

Mr. Vijaykanth Tummalapally performed some useful numerical studies of single-particle orbits in combined helical wiggler and axial guide magnetic fields during the spring and summer of 1990. Again, the recently-acquired IBM R6000 workstation will be valuable in the continuation of this project. Particle simulations of a non-cold helical electron beam near orbital instability are needed to resolve the complicated and disparate orbital dynamics and the concomitant emitted radiation.

Establishment of Computer Research Laboratory

The Principal Investigator has installed the computer hardware purchased through this grant in his newly-established computer research laboratory located in Room 301A of Just Science Hall, adjacent to his office, Room 301B. The following equipment was purchased:

1. An Everex 386/33 Mhz with 8 MB RAM and 330 MB hard disk.
2. An Intel 80387 math coprocessor.
3. A Weitek 3167 coprocessor.
4. A dual-coprocessor board.
5. A NEC Multisync 5D color monitor.
6. A NEC graphics card.
7. A NEC 890XL PostScript laser printer.
8. An IBM PS/2 Model 70 with 2 MB RAM and VGA graphics.
9. A Panasonic KX-1124 dot-matrix printer.
10. A Hewlett-Packard 7550A graphics plotter.

In addition, a variety of mathematical and programming software was acquired.

The Everex 386/33 and the IBM PS/2 will be connected via Ethernet to an IBM R6000/Model 530 workstation which was recently obtained by the PI through a separate DOE grant and which has also been installed in the computer lab. As noted earlier, the availability of the IBM RCSC machine makes feasible on expansion in scope of the present work to include large particle simulations.

Future Work:

The research objectives of this grant (see Appendix B) were proposed in the context of a three-year proposal and many of them remain to be addressed. Continuing support of this work by AFOSR has been requested. In any event, the PI considers the computer capability provided by this grant to be vital to his continued research productivity.

Appendix B: Summary of Research Objectives

Project 1: Sideband Control by Optical Guiding

1. A determination of group velocity in the nonlinear saturated regime. The analytic model of this regime due to Antonsen and Levush is appealing in its mathematical tractability but it is not yet clear how to accommodate the concept of group velocity within that framework.

2. A mathematical investigation of the limitations of the group-velocity concept in the presence of gain.

3. An extension of the analysis to include space-charge effects and waveguide boundary conditions.

4. An analytic and numerical study of the sensitivity of the control condition to the distribution of trapped orbits.

5. An investigation of sideband seeding at saturation and the conditions for the validity of the conventional linear theory. This issue will involve the analysis of a certain Mathieu equation.

6. An investigation of multiple sideband generation by parametric coupling. Although there has been some limited study in the engineering literature of combined parametric and forcing excitation of nonlinear systems, this past work is restricted to the case of steady-state oscillations and weak nonlinearity.

Project 2: A Path to Ultra-High-Power Free-Electron Lasers

1. Inclusion of the radiation field E_r in the Lorentz-Dirac equation of motion. The neglect E_r is inappropriate if the ponderomotive force becomes competitive with the constant field E_o, the condition for this being $E_r \gtrsim 2\gamma_\infty E_o/Kw$.

2. A careful analytic and numerical study of the bunch degradation issue. Derivation of an upper bound on the permissible interaction length.

3. Relaxation of the assumption $\rho/\gamma_\infty \ll \lambda$ and inclusion of the effects of transverse interference across the face of the disk. A proper treatment of a radiating charged structure would be reminiscent of the old extended-electron theories. Is such a disk stable or subject to clumping on smaller scales?

4. Investigation of the prospects for optical guiding in the class of laboratory devices considered here.

5. Further analysis of the scheme of frozen microbunches proposed by Yu as a means of preserving the integrity of the macroparticle model.

6. Inclusion of a guide magnetic field B_o in the Lorentz-Dirac equation of motion. Further mathematical analysis of the conditions for minimum axial degradation and for immunity to saturation by trapping.

Project 3: The Orbital-Instability Operating Point

1. A thorough analytic investigation of the emission of radiation by an electron beam with a nonzero energy spread near the point of exponential instability of the helical orbits.

2. A clarification and exploitation of mathematical analogies with the theory of radio-frequency heating of nonuniform plasmas by phase mixing.

3. The use of a helical-ribbon model for the electron beam in a gain calculation which includes both radial gradients and a finite energy spread.

4. The analysis of velocity-shear instabilities associated with the ribbon model.

5. Exploration of a new concept: A dual-beam free-electron laser consisting of a primary electron beam coupled to a concentric tenuous control beam near orbital instability. It has been shown by Stenflo for a one-dimensional wiggler field that the presence of a tenuous secondary electron beam near orbital instability can destabilize the electrostatic plasma mode suppoted by the primary electron beam. The implication is that such a tenuous control beam could thereby enhance the gain in a Raman free-electron laser. To assess this possibility, it is necessary to perform a three-dimensional analysis which takes account of the radial variation of the wiggler field. The primary and secondary electron beams then no longer physically overlap in space, but instead have different radial locations according to their energies. However, in a cylindrical waveguide, the beams remain coupled by the boundary conditions on the fields. Does the instability persist in these circumstances? The appropriate dispersion relation has been derived by the PI but has not yet been solved numerically.

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Nuclear Instruments and Methods in Physics Research A296 (1990) 532-534
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HIGHER-POWER FREE-ELECTRON LASERS

Shayne JOHNSTON

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The dominant process is spontaneous emission, enhanced by prebunching on a length scale short compared with the wavelength, and sustained by a strong axial electric field. Generally speaking, the potential for very high power levels is achieved at the expense of phase coherence relative to the conventional free-electron laser.

This paper concerns a radical variant [1,2] of the free-electron laser based on enhanced and driven spontaneous emission. The essential idea is founded upon an exact mathematical solution [2] of the Lorentz–Dirac equation and on a spontaneous radiative-reaction effect which is completely omitted from the usual theoretical description of free-electron lasers. Thus, it is proposed to study a new domain in parameter space where this normally negligible effect becomes dominant.

The principal advantage of this new class of laboratory devices is the potential for very high power levels. Generally speaking, this high power is achieved at the expense of phase coherence relative to the conventional free-electron laser, although the radiation spectrum still consists of sharp emission lines with small contributions from well-separated harmonics provided the wiggler pump parameter $K_w = \Omega_w / k_w c$ satisfies $K_w < 1$, and the emission is confined to a forward cone of angular width $1/\gamma$ for highly relativistic electrons with $\gamma \gg 1$.

The ultimate power limitations inherent in free-electron laser devices are an important consideration for such proposed applications as laser propulsion of spacecraft [3], removal of chlorofluorocarbons from the earth's atmosphere [4] and, of course, antimissile defense systems. The saturation mechanism in conventional free-electron lasers is electron trapping in the coherent ponderomotive potential wells. Efficiency-enhancement schemes have been devised to prohibit the onset of saturation by tapering the wiggler magnetic-field strength or wavelength [5]. Such tapering schemes are conceptually equivalent to providing a longitudinal accelerating electric field $E_{\parallel}$ to restore the energy transferred from the electrons to the radiation, the strength of $E_{\parallel}$ being externally programmed to balance the ponderomotive force. The rough idea underlying this paper is to increase the radiated power by making $E_{\parallel}$ as large as possible. To achieve this goal, a very different kind of balance should be arranged.

The new proposed scheme has two unconventional ingredients which serve, respectively, to enhance and to sustain the spontaneous emission. The enhancement occurs because the electron beam is prebunched on a length scale which is *short* compared with the radiated wavelength. In contrast, the bunching which occurs in an ordinary free-electron laser is on the *same* length scale as the wavelength and is due to the ponderomotive force. Here, the microbunches behave as macroparticles of charge Ne and mass Nm which radiate coherently. Although the ponderomotive effect, which ~~varies as~~ e/m, is unaffected, the scattering cross section and the wiggler-radiation-pressure effect vary as e^2/m and so are enhanced by the large factor N. Consequently [6], spontaneous emission can dominate stimulated emission, and the relevant dynamical equation then becomes the Lorentz–Dirac equation including enhanced radiative reaction rather than the customary pendulum equation.

The second key ingredient, sustainment of this enhanced emission, is achieved simply by applying a strong axial electric field $E_{\parallel}$ ab initio and so pre-establishing at a very high value the level of the radiation field at which ponderomotive buckets can even form. In the meantime, a balance is automatically struck [7] in which all of the energy gained from $E_{\parallel}$ is immediately shed as enhanced spontaneous radiation at the free-electron-laser wavelength. The electrons maintain a constant energy γ_{∞} in this asymptotic state of balance [1] and act simply as a catalytic intermediary with 100% efficiency.

It is assumed that the preliminary bunching has been accomplished by utilizing a conventional saturated free-electron-laser stage which results in a train of disk-shaped structures having an axial thickness δ and a transverse radius ρ. In order to treat the electron bunch as a macro particle without extended structure, the inequalities $\delta \ll \lambda$ and $(\rho/\gamma_{\infty}) \ll \lambda$ must be satisfied, where λ denotes the radiated wavelength, $\lambda = \lambda_w(1 +$

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$K_w^2)/2\gamma_\infty^2$. The motion of the microbunches is then governed by the fully relativistic Lorentz–Dirac equation

$$\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}\tau} = -(\boldsymbol{\Omega}_E\gamma + \boldsymbol{u}\times\boldsymbol{\Omega}_B)$$

$$+ N\tau_0\left\{\frac{\mathrm{d}^2\boldsymbol{u}}{\mathrm{d}\tau^2} - \left[\left(\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}\tau}\right)^2 - \left(\frac{\mathrm{d}\gamma}{\mathrm{d}\tau}\right)^2\right]\boldsymbol{u}\right\}, \tag{1}$$

where $\boldsymbol{u} = \gamma\boldsymbol{v}/c$, τ is the proper time, $\boldsymbol{\Omega}_E = |e|\boldsymbol{E}/m_0c$, $\boldsymbol{\Omega}_B = |e|\boldsymbol{B}/m_0c$ and $\tau_0 = 2e^2/3m_0c^3$. Let the electromagnetic fields comprise a helical-wiggler magnetic field

$$\boldsymbol{\Omega}_B = \Omega_w(\hat{x}\cos k_wz + \hat{y}\sin k_wz), \tag{2}$$

and a uniform axial electric field $\boldsymbol{\Omega}_E = -\Omega_E\hat{z}$. Note that the radiated field and hence the ponderomotive force have been omitted completely from eq. (1) in accordance with the preceding discussion.

In order to solve eq. (1) explicitly, transform to a helical coordinate system which rotates with the wiggler field:

$$\hat{e}_1 = (-\hat{x}\sin k_wz + \hat{y}\cos k_wz),$$

$$\hat{e}_2 = (-\hat{x}\cos k_wz - \hat{y}\sin k_wz),$$

$$\hat{e}_3 = \hat{z},$$

and seek a solution for constant γ, u_1, u_2, u_3. One is thus led [2] to the following three conditions which define an exact steady-state solution:

$$u_1 = -N\tau_0k_wcu_3u_2(1 + u_1^2 + u_2^2), \tag{3}$$

$$u_2 = \Omega_w/k_wc + N\tau_0k_wcu_3u_1(1 + u_1^2 + u_2^2), \tag{4}$$

$$\Omega_E + \Omega_wu_1 = N\tau_0k_w^2c^2u_3^2(u_1^2 + u_2^2). \tag{5}$$

For given u_3 and upon elimination of u_1, eqs. (3) and (4) yield a cubic equation for u_2 which always has one real positive root. Condition (5) then determines the corresponding axial electric field. This exact solution reduces to the customary helical orbit when radiative-reaction corrections and E_0 are ignored.

In the limiting case $\gamma \gg 1$ and $N\tau_0k_wc \ll 1$, conditions (3)–(5) reduce to $u_1 = 0$, $u_2 \approx \Omega_w/k_wc$, and

$$\Omega_E = \gamma^2\Omega_w^2N\tau_0. \tag{6}$$

The steady-state condition (6) has a simple interpretation in the rest frame of the electron microbunch where it expresses a balance between the dc electric force and the rate at which momentum is removed from the incident wiggler field (cf. $F = I\sigma_T/c$). This latter force is independent of the radiated field level, unlike the ponderomotive force which is proportional to E_r. The new balance condition (6) sustains the helical motion of the electrons and the concomitant spontaneous emission. The static electric field is balanced not against the coherent ponderomotive force but instead against the bunch-enhanced radiation pressure force.

More remarkable than the mere existence of this steady-state solution is the fact [1] that it is an attractor: the energy $\gamma(\tau)$ always becomes asymptotically constant and equal to γ_∞, the value determined by the balance condition (6), regardless of the initial energy γ_0 or the field strengths E_0 and B_w involved. The transient length scale for the asymptotic state of balance to be achieved becomes accessible in the laboratory for N sufficiently large. The attractive character of the solution ensures that the balance is self-regulating and insensitive to small field errors.

An important constraint in the proposed scheme is the potential degradation of the microbunches due to both the initial electron energy spread and the energy spread induced subsequently by electrostatic repulsion. Initial estimates [2] suggest that the upper bound on the permissible interaction length is quite stringent. There are at least two possible ways to circumvent this limitation. One way is to adapt the idea of "frozen" microbunches as proposed by Yu [8], i.e., to satisfy simultaneously the resonance conditions for bunching and for radiation. Thus, the electrons would continue to see the bunching lasers while traversing the wiggler region and one would have $\gamma_0 = \gamma_\infty$.

A second possibility is to introduce a strong axial guide magnetic field B_0 into the wiggler region. The relation between the axial velocity v_z and the energy γ for a helical orbit then becomes [9]

$$\frac{v_z^2}{c^2} = 1 - \frac{1}{\gamma^2}\left[1 + \frac{K_w^2}{(1 - \Omega_0/\gamma k_wv_z)^2}\right], \tag{7}$$

where $\Omega_0 = |e|B_0/m_0c$. Implicit differentiation of eq. (7) then yields a condition for $\mathrm{d}v_z/\mathrm{d}\gamma$ to vanish, viz.,

$$\Omega_0/\gamma = k_wv_z(1 + K_w^{2/3}). \tag{8}$$

When the guide magnetic field satisfies condition (8), the axial degradation of the microbunches is thus minimized. The condition corresponds to a stable Type II orbit [9] on the strong-field side of magnetoresonance.

The use of an axial guide field also raises another interesting possibility. If, instead of condition (8), the guide magnetic field were chosen to satisfy

$$\frac{\Omega_0}{\gamma} = \frac{k_wv_z}{[1 - \beta_w^2(\gamma_z^2 - 1)]}, \tag{9}$$

then the ponderomotive potential can be shown to vanish [9]. Under such circumstances a conventional free-electron laser would have zero gain whereas the devices described in this paper would not only still radiate but also would be totally immune to saturation by trapping and to sideband instabilities.

In conclusion, we note some directions for further research as follows:

(1) Inclusion of the radiation field E_r in the Lorentz–Dirac equation of motion. The neglect of E_r is

inappropriate if the ponderomotive force becomes competitive with the constant field E_0, the condition for this being $E_r \geq 2\gamma_x E_0/K_w$.

(2) A careful analytic and numerical study of the bunch degradation issue. Derivation of an upper bound on the permissible interaction length.

(3) Relaxation of the assumption $\rho/\gamma_x \ll \lambda$ and inclusion of the effects of transverse interference across the face of the disk. A proper treatment of a radiating charge structure would be reminiscent of the old extended-electron theories [10]. Is such a disk stable or subject to clumping on smaller scales?

(4) Investigation of the prospects for optical guiding in the class of laboratory devices considered here.

(5) Further analysis of the scheme of frozen microbunches proposed by Yu [8] as a means of preserving the integrity of the macroparticle model.

(6) Inclusion of a guide magnetic field B_0 in the Lorentz-Dirac equation of motion. Further mathematical analysis of the conditions for minimum axial degradation [eq. (8)] and for immunity to saturation by trapping [eq. (9)].

Acknowledgements

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April 1990

A Path to Ultra-High-Power Free-Electron Lasers

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Abstract

A radical variant of the free-electron laser is proposed and analyzed. The radiation is generated by spontaneous emission, enhanced by prebunching on a length scale short compared with the wavelength, and is sustained by a driving axial electric field. In contrast with conventional efficiency-enhancement schemes which modify the pendulum equation, the electric field is here balanced against the rate at which momentum is removed from the pump field alone. An explicit solution of the Lorentz-Dirac equation governing the microbunches demonstrates that this balance is self-regulating and nonlinearly stable. A numerical example is presented of a submicron radiation source with a peak power of 33 TW. Generally speaking, the potential for very high power levels is achieved at the expense of phase coherence relative to the conventional free-electron laser.

I. Introduction

The ultimate power limitations inherent in free-electron laser devices are an important consideration for such proposed applications as laser propulsion of spacecraft[1], removal of chlorofluorocarbons from the earth's atmosphere[2] and, of course, antimissile defense systems.[3] The saturation mechanism in conventional free-electron lasers is electron trapping in the coherent ponderomotive potential produced by the beating of the wiggler and radiation fields. Efficiency-enhancement schemes have been devised to prohibit the onset of saturation by tapering the wiggler magnetic field strength or wavelength.[4] Such tapering schemes are conceptually equivalent to providing a longitudinal accelerating electric field E_0 to restore the energy transferred from the electrons to the radiation, the strength of E_0 being externally programmed to balance the ponderomotive force. The rough idea underlying this paper is to increase the radiated power by making E_0 as large as possible. To achieve this goal, a very different kind of balance should be arranged.

The scheme proposed and analyzed in this paper has two unconventional ingredients which serve respectively to enhance and to sustain the spontaneous emission. The enhancement occurs because the electron beam is prebunched on a length scale which is <u>short</u> compared with the radiated wavelength. In contrast, the bunching which occurs in an ordinary free-electron laser is on the <u>same</u> length scale as the wavelength and is due to the ponderomotive force. Here, the microbunches behave as macroparticles of charge Ne and mass Nm which radiate coherently. Although the ponderomotive effect, which varies as e/m, is unaffected, the scattering cross-section and the wiggler-radiation-pressure effect vary as e^2/m and so are enhanced by the large factor N. Consequently[5], spontaneous emission can dominate stimulated emission, and the relevant dynamical equation then becomes the Lorentz-Dirac equation including enhanced radiative

reaction rather than the customary pendulum equation.

The second key ingredient, sustainment of this enhanced emission, is achieved simply by applying a strong axial electric field E_0 ab initio and so pre-establishing at a very high value the level of the radiation field at which ponderomotive buckets can even form. In the meantime, a balance is automatically struck[6] in which all of the energy gained from E_0 is immediately shed as enhanced spontaneous radiation at the free-electron-laser wavelength. The electrons maintain a constant energy in this asymptotic state of balance[7] and act simply as a catalytic intermediary with 100% efficiency.

The paper is organized as follows. In Section II, the relativistic Lorentz-Dirac equation governing the microbunches is solved exactly to justify the preceding claims. The radiated power to be expected in such a device is discussed in Section III. The critical issue of degradation of the microbunches is examined in Section IV. A numerical example of an intense source of submicron radiation is presented in Section V. Finally, a summary of conclusions is given in Section VI.

II. Solution of the Lorentz-Dirac Equation

Consider the fully relativistic Lorentz-Dirac equation

$$\frac{d\vec{u}}{d\tau} = -\left(\vec{\Omega}_E \gamma + \vec{u} \times \vec{\Omega}_B\right) + N\tau_0 \left\{ \frac{d^2\vec{u}}{d\tau^2} - \left[\left(\frac{d\vec{u}}{d\tau}\right)^2 - \left(\frac{d\gamma}{d\tau}\right)^2 \right] \vec{u} \right\} , \quad (1)$$

where $\vec{u} = \gamma \vec{v}/c$, τ denotes proper time, $\vec{\Omega}_E = |e| \vec{E}/m_0 c$; $\vec{\Omega}_B = |e| \vec{B}/m_0 c$, and $\tau_0 = 2e^2/3m_0c^3 = 6.24 \times 10^{-24}$s. Let the electromagnetic fields comprise a helical wiggler magnetic field

$$\vec{\Omega}_B = \Omega_w \left(\hat{x} \cos k_w z + \hat{y} \sin k_w z \right) , \quad (2)$$

and a uniform axial electric field $\vec{\Omega}_E = -\Omega_E \hat{z}$. Note that the radiated field and hence the ponderomotive force have been completely omitted from Eq. (1) in accordance with the preceding discussion. We shall return to this point in Section III.

In order to solve Eq. (1), transform to a helical coordinate system which rotates with the wiggler field, i.e.,

$$\hat{e}_1 = -\hat{x} \sin k_w z + \hat{y} \cos k_w z,$$
$$\hat{e}_2 = -\hat{x} \cos k_w z - \hat{y} \sin k_w z$$
$$\hat{e}_3 = -\hat{z},$$

and seek a solution for constant γ , u_1, u_2, u_3. One is thus led to the following three conditions which define an exact steady-state solution:

$$u_1 = -N\tau_0 k_w c\, u_2 u_3 \left(1 + u_1^2 + u_2^2\right) , \tag{3}$$

$$u_2 - \Omega_w / k_w c = N\tau_0 k_w c\, u_1 u_3 \left(1 + u_1^2 + u_2^2\right) , \tag{4}$$

$$\Omega_E + \Omega_w u_1 = N\tau_0 k_w^2 c^2 u_3^3 \left(u_1^2 + u_2^2\right) . \tag{5}$$

For given u_3 and upon elimination of u_1, Eqs. (3) and (4) yield a cubic equation for u_2 which always has one real positive root. Condition (5) then determines the corresponding axial electric field. This exact solution reduces to the customary helical orbit when radiative-reaction corrections and E_0 are ignored.

In the limiting case $\gamma \gg 1$ and $N\tau_0 k_w c \ll 1$, conditions (3), (4) and (5) reduce to $u_1 \approx 0$, $u_2 \approx \Omega_w / k_w c$, and

$$\Omega_E = \gamma^2 \Omega_w^2 N\tau_0 . \tag{6}$$

The steady-state condition (6) admits a simple interpretation in the rest frame

of the electrön microbunch where it expresses a balance between the dc electric force and the rate at which momentum is removed from the incident wiggler field (cf. F = I σ_T/c). This balance sustains the helical motion and its concomitant spontaneous emission.

More remarkable than the mere existence of this steady-state solution is the fact[7] that it is an attractor: the energy $\gamma(\tau)$ always becomes asymptotically constant and equal to γ_∞, the value determined by the balance condition (6),

$$\gamma_\infty^2 = \Omega_E / (\Omega_w^2 N \tau_0) \quad , \tag{7}$$

regardless of the initial energy γ_0 or the field strengths E_0 and B_w involved. For γ >>1, the transient length scale L_∞ for this asymptotic state of balance to be achieved is given by the formula[7]

$$L_\infty = \frac{\gamma_\infty c}{\Omega_E} \ln \left(\frac{1 + \sqrt{2 - \gamma_0^2/\gamma_\infty^2}}{1 + \gamma_0/\gamma_\infty} \right) \quad , \tag{8}$$

which is accessible in the laboratory for N sufficiently large. The attractive character of the solution ensures that the balance is rugged, i.e., that it is self-regulating and insensitive to small field errors.

III. Radiated Power

Consider next the radiated power level that is attained. We assume here that the preliminary bunching has been accomplished by utilizing a conventional saturated free-electron-laser stage which results in a train of disc-shaped structures having an axial thickness δ, a transverse radius ρ and spatial separation Δ. The density of the microbunches is then limited by electrostatic repulsion to the upper bound given by Antonsen[8]. Since we have treated the electron bunch as a macroparticle without extended structure, the inequalities $(V_\infty/V_0)\,\delta \ll \lambda$ and $(\rho/\gamma_\infty) \ll \lambda$ must be satisfied, where λ denotes the radiated wavelength $\lambda = \lambda_w (1 + \Omega_w^2/k_w^2 c^2)/2\gamma_\infty^2$. Let $L_w = N_w \lambda_w$ be the length of the magnetic wiggler beyond the transient

distance (8) and let N' denote the number of macroparticles whose radiation becomes superimposed during a wiggler transit time. Since $N' = (c - v_\infty)(L_w/c)/(v_\infty/v_0)$ it follows that

$$N' = \frac{\lambda}{(v_\infty/v_0)\,\Delta}\, N_w \qquad (9)$$

In the absence of saturation, the power radiated by the train is then sustained for a time equal to the length of the remainder of the train at the level

$$P = \frac{N' N\, |e|\, E_0\, v_\infty}{(1 - v_\infty/c)} \,. \qquad (10)$$

The factor N' in Eq. (10) ignores the regular spacing of the microbunches; it is correct in the limit in which the parameter $(v_\infty/v_0)(\Delta/\lambda)$ tends to zero, being otherwise an underestimate. The large factor $(1 - v_\infty/c)^{-1}$ is associated with time dilation[9] and has been noted previously by the author.[5]

The radiated power (10) emanates from a single train of macroparticles. If the laser bunching stage is pulsed repetitively in coordination with the electron source, then a sequence of radiating trains will traverse the wiggler, one after another. At this point, we have a superradiant source with the potential for high average power. Although the emission process is spontaneous rather than stimulated, nevertheless the radiation spectrum will consist of sharp emission lines with small contributions from well-separated harmonics provided the wiggler pump parameter $K_w = \Omega_w/k_w c$ satifies $K_w<1$. For highly relativistic electrons with $\gamma \gg 1$, the emission is confined to a forward cone of angular width $1/\gamma$. Compared with a conventional free-electron-laser amplifier, the basic trade-off here is to gain power at the expense of phase coherence.

Alternatively, for higher peak power, an oscillator configuration is possible in which the radiation from successive trains is stored between mirrors in a cavity and the intracavity power allowed to grow. It is then natural to enquire about

the power level at which the neglect of the radiation field E_r in the equation of motion (1) becomes questionable. The condition that the ponderomotive force become competitive with the constant field E_0 can be written

$$E_r \gtrsim 2\gamma_{00} E_0 / K_w \gg E_0 \quad , \tag{11}$$

with the corresponding ambient power level being $P = c\,(E_r^2/8\pi)(\pi w^2)$ where w denotes the radiation waist. If the intracavity power reached this level, the device would then operate as a conventional free-electron laser, bunching the macroparticles and saturating shortly thereafter. In order to generate coherent radiation by stimulated emission, i.e., to extract net gain from the exactly resonant macroparticles, one would now increase the electric field E_0 with a programmed time dependence $E_0(t)$ in the spirit of conventional tapering.

Note that in an ordinary high-gain free-electron laser, one seeks to maintain $w \sim \rho$ (e.g., by optical guiding) since the gain mechanism requires the presence of the radiation field. In the present scheme, however, it is desirable (and inevitable via diffraction) to have $w \gg \rho$ to reduce E_r. The critical power level corresponding to Eq. (11) exceeds the saturated power in an untapered high-gain free-electron laser[10] when the large factor $(w/\rho)^2$ is taken into account.

IV. Integrity of the Microbunches

An important constraint in the present scheme is the potential degradation of the microbunches due both to the initial electron energy spread $\Delta\gamma_0$ and to the energy spread induced subsequently by electrostatic repulsion. The axial velocity v_z depends on γ according to the relation $(v_z^2/c^2) = [1-(1+K_w^2)/\gamma^2]$, and thus an energy spread $(\Delta\gamma/\gamma)$ implies a corresponding velocity spread

$$\frac{\Delta v_z}{v_z} \sim \frac{c^2}{v_z^2}\,\frac{(1+K_w^2)}{\gamma^2}\,\frac{\Delta\gamma}{\gamma} \quad , \tag{12}$$

which translates to axial spreading in space. The macroparticle model breaks down when the axial spreading Δz becomes on the order of the spacing Δ and the distance L_d for this to happen can be determined from the formula[11]

$$L_d = \frac{\gamma^3}{(1+K_w^2)} \frac{v_z^2}{c^2} \int_{\delta_0}^{(\delta_0+\Delta)} \frac{d\delta}{\left[2(\Delta\gamma_0) + \int_{\delta_0}^{\delta} \frac{|e|\hat{E}(\delta')}{m_0 c^2} d\delta'\right]} , \quad (13)$$

where $\hat{E}(\delta)$ denotes the longitudinal self electric field of the microbunch.[12]

Formula (13) represents a stringent upper bound on the permissible interaction length ($L_\infty + L_W$). However, there are at least two possible ways to circumvent this limitation. One way is to adapt the idea of "frozen" microbunches as proposed by Yu[13], i.e., to satisfy simultaneously the resonance conditions for prebunching and for radiation. Thus, the electrons would continue to see the bunching lasers while traversing the wiggler region and radiating, and one would have $\gamma_0 = \gamma_\infty$ with $L_\infty \to 0$.

A second possibility[14] is to introduce a strong axial guide magnetic field B_0 into the wiggler region. The relation between the axial velocity V_z and the energy γ for a helical orbit then becomes[15]

$$\frac{v_z^2}{c^2} = 1 - \frac{1}{\gamma^2}\left[1 + \frac{K_w^2}{(1 - \Omega_0/\gamma k_w v_z)^2}\right] , \quad (14)$$

where $\Omega_0 = |e| B_0 / m_0 c$. Implicit differentiation of Eq. (14) then yields a condition for $dv_z / d\gamma$ to vanish, viz.,

$$\Omega_0/\gamma = k_w v_z \left(1 + K_w^{2/3}\right) . \quad (15)$$

When the guide magnetic field satisfies condition (15), the axial degradation of the microbunches is thus minimized. The condition corresponds to a stable Type II orbit[15] on the strong-field side of magnetoresonance.

V. Numerical Example of an Intense Submicron Source

The following numerical example assumes the coexistence of state-of-the art technologies without any consideration of the details of the experimental configuration. The purpose of the example is simply to emphasize the potential for high power in the class of devices considered.

Consider an electron beam as designed by Barletta[16] for use in a laboratory x-ray laser. We take $\gamma = 688$ (i.e., approximately one-third the design energy), but otherwise adopt the remaining design parameters as follows: bunch length 1.2 ps, bunch spacing 0.26 ns, number of bunches 5, repetition rate 200 Hz, number of particles per bunch 7.2×10^{9}, normalized emittance 0.001 mm-rad, focused transverse radius 24.1 μm and energy spread $(\Delta\gamma/\gamma) = 0.1\%$.

Let the formation of microbunches now be accomplished by beating on intense KrF laser (wavelength 0.248 μm, power 2GW, pulse length 12 ns) against a helical magnetic wiggler ($K_w' = 1$, $\lambda_w' = 11.7$ cm). The electrons are resonant with the beat potential and will bunch to form macroparticles with $N = 4.5 \times 10^{6}$ and $\delta < \Delta \sim 0.25\ \mu m$. Next, we hold these microbunches frozen by allowing the prebunching fields to extend into the primary wiggler region. The primary wiggler (co-wound with the bunching wiggler) is taken to have $\lambda_w = 20$ cm, $K_w = 1$ and $L_w = 16.0$ m. Intense radiation is then emitted at the wavelength $\lambda = 0.42\ \mu$m.

The accelerating electric field E_o required to sustain this radiation is found from Eq. (6) to be $E_o = 2 \times 10^{8}$ V/m. The scheme considered here converts all of the work done by this state-of-the art[17] accelerating gradient to submicron radiation. The corresponding peak power is, from Eq. (10), an immense 33 TW,

emitted in 1.2 ps pulses at a repetition rate of 1000 pulses per second.

VI. Conclusion

This paper has addressed a general question about free-electron lasers, viz., what are the ultimate power limitations inherent in this emerging new technology? It is clear that the optimum arrangement would be to apply the maximum possible accelerating gradient to the electrons and then to convert all of this work to radiation with 100% efficiency. A conventional tapered free-electron laser can't reach this optimum state because it is governed by the physics of saturation by trapping which leads to the result that E(taper) is much smaller that E (state of the art). This paper has analyzed an alternative scheme by which the optimum state can indeed be attained.

As illustrated in the numerical example in Section V, the frozen-microbunch version of the scheme requires the existence of a powerful laser with a wavelength shorter than that which one desires to generate. The principal advantage of this new class of devices is high power. Generally speaking, the potential for very high power levels is achieved at the expense of phase coherence relative to the conventional free-electron laser.

Acknowledgment

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Higher-Power Free-Electron Lasers

Shayne Johnston
Jackson State University
Jackson, Mississippi

The dominant process is spontaneous emission, enhanced by prebunching on a length scale short compared with the wavelength, and sustained by a strong axial electric field. Generally speaking, the potential for very high power levels is achieved at the expense of phase coherence relative to the conventional free-electron laser.

Conventional FEL

$\boxed{\text{Spontaneous scattering}} \ll \boxed{\text{Stimulated scattering}}$

S. Johnston + R.M. Kulsrud, Phys. Fluids 1977

Rate at which momentum is removed from pump field (radiation pressure) $\propto \left(\frac{e^2}{m}\right) B_w^2$

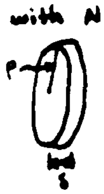
Ponderomotive (pendulum) beat force $\propto \left(\frac{e}{m}\right) B_w E_{rad}$

$\boxed{\text{Radical FEL}: \quad \gg}$

* Prebunch electron beam on length scale which is SHORT compared with λ.

Microbunches (Ne^-) with $N \gg 1$.

Train of disc-shaped macroparticles, each with N electrons.



$\delta \ll \lambda \qquad \frac{\rho}{\gamma} \ll \lambda$

$\frac{\lambda_w(1+K_w^2)}{2\gamma^2}$

Spacing $\Delta \ll \lambda$

$\underline{\gamma \gg 1}$

$$\frac{\gamma(\tau)}{\gamma_0} = \frac{e^{\Omega_e \tau}}{\sqrt{1 + \left(\frac{\gamma_0^2}{\gamma_\infty^2}\right)\left(e^{2\Omega_e \tau} - 1 + \mu \Omega_e \tau\right)}}$$

Spontaneous-emission radiation source (a "laser"?)

$$\lambda = \frac{\lambda_w(1+K_w^2)}{2\gamma^2} \qquad \gamma \gg 1 \qquad K_w < 1$$

$$\frac{\Delta\omega}{\omega} \sim \frac{\pi}{2N_w} \qquad \Delta\theta < \frac{1}{\gamma}$$

Microbunches (Ne^-) $\xrightarrow{\gamma}$ B_w $E_0 \longleftarrow$

$\gamma \rightarrow \gamma_\infty$ (constant) for $z > L_\infty$

Self-regulating balance.

Accessible in laboratory for $N \gg 1$.

Work done by E_0 $\xRightarrow{100\%}$ efficiency Spontaneous radiation

$$\mu = \frac{2\Omega_0^2 - \Omega_w^2}{\gamma_\infty^2 \Omega_e^2} \qquad \boxed{\gamma_\infty = \sqrt{\frac{\Omega_e}{N \Omega_w^2 \tau_0}}}$$

$\gamma \rightarrow \gamma_\infty$ as $\tau \rightarrow \infty$

independent of γ_0

$$L_\infty = \frac{\gamma_\infty c}{\Omega_e} \ln\left(\frac{1 + \sqrt{2 - \gamma_0^2/\gamma_\infty^2}}{\left(1 + \frac{\gamma_0}{\gamma_\infty}\right)}\right)$$

<u>Lorentz-Dirac Equation</u>

$$\frac{d\vec u}{d\tau} = -(\vec\Omega_E \gamma + \vec u \times \vec\Omega_B) + \tau_0\left\{\frac{d^2\vec u}{d\tau^2} - \left[\left(\frac{d\vec u}{d\tau}\right)^2 - \left(\frac{d\gamma}{d\tau}\right)^2\right]\vec u\right\} .$$

where $\vec u = \gamma \frac{\vec v}{c}$, $\tau_0 = \frac{2}{3}\frac{e^2}{m_0 c^2}N$,

$\vec\Omega_E = \frac{|e|\vec E}{mc}$, $\vec\Omega_B = \frac{|e|\vec B}{mc}$.

<u>Exact Solution for B_w, E_z</u>

$\vec E = -E_0\hat z$, $\vec B = B_w(\hat x\cos k_w z + \hat y \sin k_w z)$

$$\begin{cases} \hat e_1 = -\hat x \sin k_w z + \hat y\cos k_w z \\ \hat e_2 = -\hat x\cos k_w z - \hat y \sin k_w z \\ \hat e_3 = \hat z \end{cases}$$

Seek solution for constant γ, u_1, u_2, u_3 .

<u>Exact steady-state solution</u> :

- $u_1 = -k_w c\tau_0 u_2 u_3 (1+u_1^2+u_2^2)$
- $u_2 - K_w = k_w c\tau_0 u_1 u_3(1+u_1^2+u_2^2)$

  For given u_3 , cubic equation for u_2 always has one real positive root.

- $\frac{\Omega_E}{k_w c} + K_w u_1 = k_w c\tau_0 u_3^3(u_1^2+u_2^2)$

  determines axial electric field.

<u>$\gamma \gg 1$, $k_w c\tau_0 \ll 1$</u>

$u_1 \approx 0$ $\quad u_2 \approx K_w$

$$\boxed{\Omega_E = \gamma^2\Omega_w^2\tau_0 \, !}$$

cf. $F = \frac{I\mathcal{E}}{c}$

- Scheme is self-regulating and nonlinearly stable. Steady-state solution is an <u>attractor</u>
- Prebunch electron beam on length scale <u>small</u> compared with radiated wavelength.

<u>Power radiated by train</u>:

$$P = \frac{N'N|e|E_0 V_\infty}{(1 - V_\infty/c)}$$

N' = # of macroparticles whose radiation becomes superimposed during a wiggler transit time.

<u>Condition for neglect of ponderomotive force</u>

$$E_p \lesssim \frac{2\gamma_\infty E_0}{K_w}$$

<u>Length scale for macroparticle degradation</u>

$$L_d = \frac{\gamma^3}{(1+K_w^2)}\frac{v_z^2}{c^2}\int_{\delta_0}^{(\delta_0+\Delta)} \frac{d\delta}{\left[2(\Delta E_0) + \int_{\delta_0}^{\delta}\frac{|e|\hat E(\delta')}{mc^2}d\delta'\right]}$$

$\hat E(\delta)$ = longitudinal self electric field of the microbunch.

<u>Inclusion of guide magnetic field</u>

Helical orbit condition

$$\frac{v_z^2}{c^2} = 1 - \frac{1}{\gamma^2}\left[1 + \frac{K_w^2}{\left(1-\frac{\Omega_0}{\gamma k_w v_z}\right)^2}\right] .$$

- Condition for $\frac{dv_z}{d\gamma}\to 0$:

  (minimum axial degradation)

  $$\frac{\Omega_0}{\gamma} = k_w v_z (1+K_w^{2/3}) .$$ Strong field

  Type II orbit – Stable, on far side of magnetoresonance

- Condition for zero ponderomotive force: (immunity to saturation by trapping)

$$\frac{\Omega_0}{\gamma} = \frac{k_w v_z}{[1-\beta_w^2(\gamma_z^2-1)]}$$

free-electron laser is studied theoretically and experimentally. Two complimentary theoretical approaches to the problem of optical guiding in a waveguide containing a filamentary electron beam are given and shown to be in good agreement with each other in the exponential gain regime. Evidence for optical guiding of 2 mm-wavelength radiation along the electron beam in the Columbia FEL is obtained experimentally by analysis of spatial "ringdown" data and compared with numerical simulations. Data is presented for both the exponential gain and saturation regimes. The optical guiding effect at saturation is found to be significantly weaker and can be detected by a slight enhancement in the sideband shift.

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3T 8 Millimeter Wavelength Metal Grating Free Electron Laser, Y. Fisher, A. Fisher, E. Garate, University of California, Irvine.—Preliminary experimental results of a metal grating free electron laser designed to operate in the lower millimeter (2-3) wavelength regime and using overmoded Bragg reflectors will be presented. The device consists of two opposing planar gratings which form a slow wave supporting structure, interacting with a mildly relativistic electron beam. The electron beam is generated using a rectilinear Pierce geometry diode and a thermionic cathode capable of producing an electron beam with a current density of ~6A/cm². The electron accelerating voltage can be varied up to 25KV and has a pulse duration of 5us. A theoretical discussion of the gain and output radiation wavelength dependence on the grating parameters will also be presented.

* 3T 9 Enhanced Sustained Spontaneous Emission with Guide Magnetic Field. S. Johnston, Jackson State University -- The potential role of a guide magnetic field in an unconventional free-electron-laser scheme[1] is studied. The dominant process in this scheme is intense spontaneous emission, enhanced by prebunching on a length scale short compared with the wavelength, and sustained by a strong axial electric field. It is shown that the guide magnetic field can be tuned either to minimize axial degradation of the microbunches ($dv_z/d\gamma \rightarrow 0$) or to cause the ponderomotive potential to vanish. In the latter case, a conventional FEL would have zero gain whereas the devices considered here would not only still radiate but would be totally immune to saturation by trapping and to sideband instabilities.

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3T 10 Interaction of High and Low Frequency Waves in a Free Electron Laser.* N. METZLER, P. E. LATHAM, T. M. ANTONSEN, and B. LEVUSH, LPR, University of Maryland, College Park, MD.–Under certain circumstances a free electron laser can operate at two widely spaced frequencies. For example, with a planar wiggler amplification will occur at odd harmonics of the fundamental frequency. A second example is the case in which the interaction occurs in a waveguide with a sufficiently high cut-off frequency giving rise to two intersections of the beam and waveguide dispersion curves. We have studied the competition of the low and high frequency waves in both amplifier and oscillator configurations. We have found parameter regimes where the presence of a high frequency wave nonlinearly suppresses the growth of the low frequency solution. The theory predicts the ratio of cavity Q's required to insure stable operation of the high frequency mode in an oscillator as well as the useful gain for the high frequency mode in amplifier.

*This work was supported by ONR and DOE.

3T 11
Experimental Studies of Relativistic Sheet Beams and Short-Period Wigglers for a Free Electron Laser,* D.J. Radack, J.H. Booske, Y. Carmel, W.W. Destler, T.M. Antonsen, Jr., V.L. Granatstein, I.D. Mayergoyz, R.H. Jackson,† and H. Bluem, Univ. of Maryland — We present the results of recent experimental studies of short-period ($\ell_w = 1$ cm) electromagnet wigglers and the propagation of relativistic sheet electron beams through these wigglers. We have studied wiggler field uniformity as a function of mechanical tolerances and alternate magnet configurations. Two critical issues for high average power (~ 1 MW) wiggler-focused sheet beam FELs are beam stability and beam interception by the waveguide walls. We present experimental measurements on both of these issues as well as analytic theory relating intercepted current to beam parameters. Experimental verification of the theory is reported. Finally, the first observation of wiggler-induced radiation was obtained from the sheet beam FEL in an oscillator configuration.

*Supported by SDIO/IST/ONR through a contract administered by Harry Diamond Laboratories and the U.S. DoE.

†Naval Research Laboratory

3T 12
A Comparative Scaling Study of Harmonic and Fundamental Free Electron Lasers,* J.H. BOOSKE and B. LEVUSH, University of Maryland—For many of the myriad possible applications of Free Electron Lasers (FELs), a premium is placed on maximizing the frequency at fixed voltage or minimizing the beam voltage at fixed frequency. With convenient normalizations, some simple scaling relations and a general calculation of coupling coefficients, we discuss the quantitative tradeoffs between using short period wigglers for fundamental interaction versus harmonic operation with more conventional wigglers.

* Work supported by ONR and U.S. DoE.

3T 13
Designs and Experiments for High Average Power FELs Using Sheet Electron Beams and Short Period Wigglers,* S.W. Bidwell, J.H. Booske, Y. Carmel, Z.X. Zhang, D.J. Radack, T.M. Antonsen, Jr., V.L. Granatstein, B. Levush, W.W. Destler, P.E. Latham, and I.D. Mayergoyz, University of Maryland, and H.P. Freund, Science Applications International Corporation — We will discuss designs and feasibility studies for a high average power (~ 1 MW) millimeter-wave (150-600 GHz) FEL using a short-period wiggler ($\ell_w \sim 1$ cm) and a sheet electron beam ($V_b \sim 0.5$ - 1.0 MV). Analyses include considerations of cavity wall heating, high voltage electron gun design, mode control, etc. We will also present preliminary results of experiments on a sheet beam FEL oscillator utilizing a 100 ns, 300-600 kV pulse-line accelerator.

* Supported by the U.S. Department of Energy and SDIO/IST through a contract administered by the Harry Diamond Laboratories.